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Neotectonics in the Strait of Georgia: first tentative correlation of seismicity with shallow geological structure in southwestern British Columbia

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Abstract: Multichannel seismic reflection data within the Strait of Georgia provide the first tentative correlation of geological structure with recent seismicity. Reflection data show broad folding of sedimentary rocks in the southernmost part of the strait. To the north are two broad (5–10 km wide) deformation zones with interpreted normal faults. Both zones have an associated magnetic anomaly. The northern deformation zone, 30 km west of Vancouver, correlates with the location of a number of recent shallow earthquakes. Detailed analyses of an M=4.6 event at this site (June 1997) describe a shallow (2–4 km depth) reverse thrust on a northern dipping (~50°), east-trending fault plane. The fault dip direction and strike agree with seismic reflection interpretations and the magnetic anomaly trend. These data are required to provide fundamental geological information for addressing issues of strain partitioning in the Cascadia forearc.

Résumé : Des données de sismique-réflexion multicanal recueillies dans le détroit de Georgia nous permettent d'établir pour la première fois des corrélations possibles entre des structures géologiques et l'activité séismique récente. Les données de sismique-réflexion révèlent que les roches sédimentaires de la partie la plus méridionale du détroit sont déformées par de grands plis ouverts. Au nord, on reconnaît deux grandes zones de déformation (larges de 5 à 10 km) que l'on assimile à des failles normales. À chacune de ces deux zones est associée une anomalie magnétique. La zone de déformation du nord, à 30 km à l'ouest de Vancouver, est mise en corrélation avec le lieu où sont survenus depuis peu un certain nombre de séismes peu profonds. Des analyses détaillées d'un séisme de magnitude 4,6 qui a eu lieu à cet endroit en juin 1997 révèlent l'existence d'un mouvement de chevauchement à faible profondeur (de 2 à 4 km), le long d'une surface de faille de direction est inclinée vers le nord. La direction et le pendage de la faille concordent avec les interprétations dérivées de la sismique-réflexion et avec l'orientation de l'anomalie magnétique. L'acquisition de ces données est nécessaire à la constitution de l'information géologique de base pour l'étude de la répartition des contraintes dans l'avant-arc de Cascadia.

INTRODUCTION

Southwestern British Columbia and the United States Pacific Northwest have been subjected to a number of large, damaging earthquakes during historic times. Despite the vast destruction possible when an earthquake occurs on a shallow crustal fault near an urban area, fundamental information about crustal and subcrustal earthquakes occurring in southwestern British Columbia and the Pacific Northwest is lacking. To better understand the seismic hazards in this region, it is necessary to map the subsurface structure and to identify faults and other evidence of tectonic activity. With this rationale, a large, multidisciplinary seismic survey was undertaken in March 1998 through Puget Sound, the Juan de Fuca Strait, and the Strait of Georgia. The experiment, referred to as SHIPS (Seismic Hazard Investigations in Puget Sound), was conducted by a consortium of United States and Canadian institutions and universities (*see* Fisher et al., 1999).

Multichannel seismic (MCS) reflection data from the Strait of Georgia have been processed to extract as much high-resolution information as possible from the top 4 seconds (two-way traveltime) of the seismic records. The focus was to image the shallow structure of the Georgia Basin and, in particular, to investigate the epicentral region of a magnitude 4.6 earthquake that occurred beneath the Strait of Georgia, 30 km to the west of Vancouver on June 24, 1997 (Fig. 1). This region has a history of concentrated shallow (<6 km depth) seismicity, including an M=4.9 earthquake in 1975. Data from detailed studies of the June 1997 earthquake, seismic reflection data, and airborne magnetic data are presented as part of this investigation.

BACKGROUND GEOLOGY AND TECTONIC SETTING

Georgia Basin is one of a series of sedimentary basins on the Pacific margin of North America, which initially developed in a convergent-margin setting during the late Mesozoic (Dickinson, 1976). The sediments in Georgia Basin are siliciclastic, locally attaining a thickness in excess of 6 km and distributed over an area of approximately 25 000 km^2. Monger (1990, 1991), Hamilton (1991), Mustard (1991), Mustard and Rouse (1994), England and Bustin (1998), and Mosher and Hamilton (1998) have conducted the most comprehensive studies of the Georgia Basin to date. It is a Cretaceous to Cenozoic forearc basin that overlaps the Wrangellian part of Vancouver Island to the west and the Coast Belt to the east (Monger, 1990). It overlies the presently subducting oceanic Juan de Fuca Plate. A thick (3–9 km) sedimentary (marine and nonmarine) package has accumulated during two major phases of basin subsidence (England and Bustin, 1998). The first phase occurred in the Late Cretaceous (Nanaimo Group) and the second in the Late Paleocene to Late Eocene (Huntingdon and Chuckanut formations). Since Eocene time, an increasingly oblique and diminished rate of plate

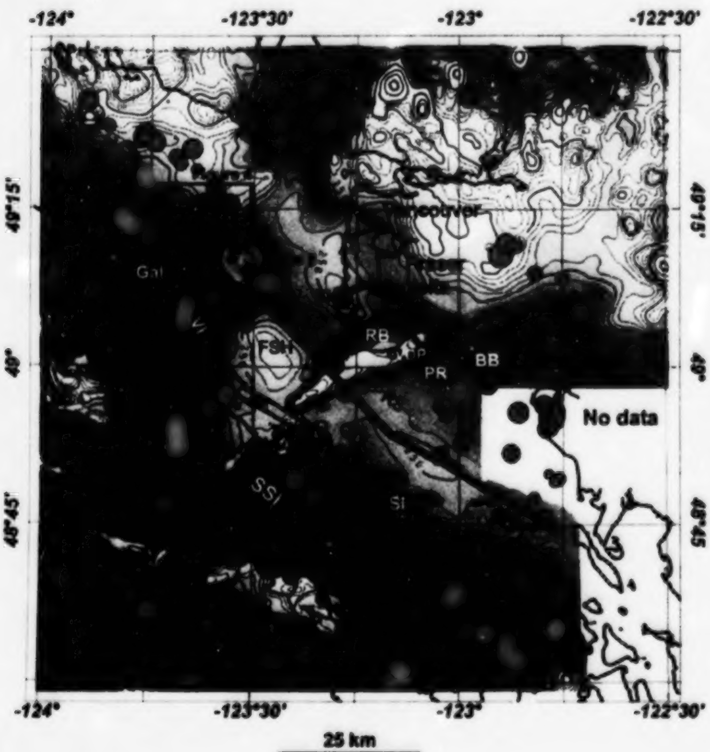

Figure 1.

Location diagram with SHIPS track, magnetic anomalies and regional 10-year seismicity. Aeromagnetic data range from -500 nT (black) in the southwest to +1660 nT (white) in the northeast. The prominent, narrow, northeast-trending intense (>600 nT) magnetic high which extends from Roberts Bank (RB) on the mainland, across the Strait of Georgia demarcates the location of DC hydroelectric cables. Seismicity data for crustal earthquakes (<35 km depth) from the period 1981–1991 are plotted, the magnitude of the earthquake proportional to the size of the dot. All events are less than M=3.5. The following abbreviations are used: SSI (Saltspring Island), SI (Saturna Island), GI (Galiano Island), VI (Valdez Island), Gal (Gabriola Island), BB (Boundary Bay), PR (Point Roberts), RS (Roberts swell), RB (Roberts Bank), VDP (Vancouver Deltaport), FSH (Foreslope hills), and SH (Sand Heads).

convergence has resulted in widespread basin uplift and erosion of western Georgia Basin. Only the Strait of Georgia remains as a remnant of the basin.

Georgia Basin remains in the arc-trench gap of the Cascadia subduction zone. The entire region is under strain resulting from eastward subduction of the Juan de Fuca Plate beneath the North American Plate (Dragert et al., 1994, 1995; Dragert and Hyndman, 1995; Henton et al., 1998). The rate of plate convergence is approximately 45 mm/year and maximum crustal shortening, as determined by geodetic measurements, is margin normal. The direction of maximum crustal stress, however, is margin parallel (Wang et al., 1995; Wang, in press). This conclusion comes from focal mechanism solutions and shear-wave anistropy studies of recent earthquakes in the Pacific Northwest and southwestern British Columbia (Wang et al., 1995; Cassidy and Bostock, 1996; Wang, in press), and from borehole breakout data from a number of wells in western Oregon (Werner et al., 1991) and western Washington State (Magee and Zoback, 1992).

Evidence of Neogene and Quaternary faulting and folding constrain the regional state of stress at much larger time scales than the stress measurements cited above. These data are, therefore, important in providing information on the regional tectonic background and history prior to the modern stress regime. Zoback and Zoback (1991) and Werner et al. (1991) summarized the neotectonic evidence for north-south compression in the Pacific Northwest. More recent studies include documentation of east-trending reverse or thrust faulting and fold structures under north-south compression in Washington State (Bucknam et al., 1992; Johnson et al., 1994, 1999; McCrory, 1996), and kinematically constrained north-south shortening of the Cascadia forearc (Wells et al., 1998). Journeay and Morrison (1999) investigated structures in southwestern British Columbia and document a case for Neogene margin-parallel elongation of the forearc by dextral transtension. No Quaternary evidence for margin-parallel tectonics has been documented on the Canadian side of the Cascadia forearc, however. Seismic reflection programs, such as SHIPS, have been undertaken to investigate the geological structure beneath this region. Prior to this research, crustal seismic activity has not been correlated with any shallow geological structures in southwestern British Columbia.

METHODS

Seismic reflection

SHIPS multichannel seismic reflection data were collected with a 6700 cubic inch, 12-gun source array, and a 96-channel, 2375 m long hydrophone array. Channel spacing is 25 m. The near 48 channels were processed to four seconds two-way traveltime depth, for the data presented in this report. Shot spacing was 50 m, resulting in a common midpoint spacing of 12.5 m and a 24-fold stack of the data. Data were bandpass filtered at 0–80 Hz.

Single channel seismic reflection data presented in this report were collected with a 20 cubic inch, 2-gun source array and recorded on a single channel, 12-element hydrophone array (*see* Mosher et al., 1998). Data were digitized at a rate of 40 μs. Processing included geometrical spreading correction and bandpass filtering (60–1500 Hz).

Earthquake studies

The M=4.6 earthquake of June 24, 1997 provides an excellent opportunity to image an active fault. This earthquake occurred at a shallow depth (<6 km) beneath the Strait of Georgia. It was preceded by a felt foreshock (M=3.4) and followed by numerous small (M=0.3–1.8) aftershocks. It was recorded on modern, digital seismographs that were well distributed in azimuth around the earthquake.

Two techniques were combined in an attempt to identify the active fault associated with this earthquake sequence; 1) determination of focal mechanisms for the largest earthquakes, to estimate the nature and orientation of the earthquake rupture; and 2) relocation of the mainshock, foreshock, and 59 small aftershocks, using waveform cross correlation (VanDecar and Crosson, 1990) to obtain precise relative P-wave and S-wave arrival times and the joint hypocentral determination program VELEST (Ellsworth, 1977; Roecker, 1981) to obtain precise relative earthquake locations. *See* Cassidy et al. (in press) for more information on these analytic methods.

Aeromagnetic studies

The study area is covered by regional magnetic data acquired during a number of different airborne surveys flown between 1962 and 1986. Data from these individual surveys have been processed, merged, and computationally draped to a datum 305 m above terrain. Data resolution is governed ultimately by flight parameters of the original surveys, which were typically flown at altitudes of 305 m to 1524 m on flight lines, which were spaced 1000–1500 m apart.

RESULTS

Seismic reflection

A total of 995 line-kilometres of MCS reflection data were collected during the SHIPS experiment. Over 100 line-kilometres were collected in the Strait of Georgia, which form the basis of this report (Fig. 1). This seismic profile, shown in Figure 2, has been assigned four seismostratigraphic units. The basal unit (unit 1) is represented by a package of coherent, largely parallel reflectors. This characteristic extends from the southern extent of the SHIPS line to the northern end of the Foreslope hills (Fig. 1). It suggests that the unit is composed of a thick (>8 km) sequence of bedded sedimentary rocks, likely of the Tertiary Huntingdon and Chuckanut formations overlying the Nanaimo Group (*see* England and Bustin, 1998). These reflectors are gently folded, with two obvious fault offsets at the south end.

The seismic character of unit 1 changes significantly north of the Foreslope hills, with a general loss in coherency of reflectors (Fig. 2). This loss in coherency is evident at two

distinct intervals, each 5–8 km wide (DZ1, DZ2, Fig. 2). Reflectors are disrupted, offset, and dipping at various angles and directions. The most coherent reflectors have an apparent maximum southward dip of about 20°E. Reflector offsets within these zones appear to describe listric normal or normal faults. It is not known whether this general change in character is a result of different rock types or related to significant deformation of the same formations as exist to the south.

Unit 2 stratigraphically overlies unit 1. Its seismic character is relatively transparent and the unit is variable in occurrence and thickness. Unit 2 is interpreted as resulting from grounding

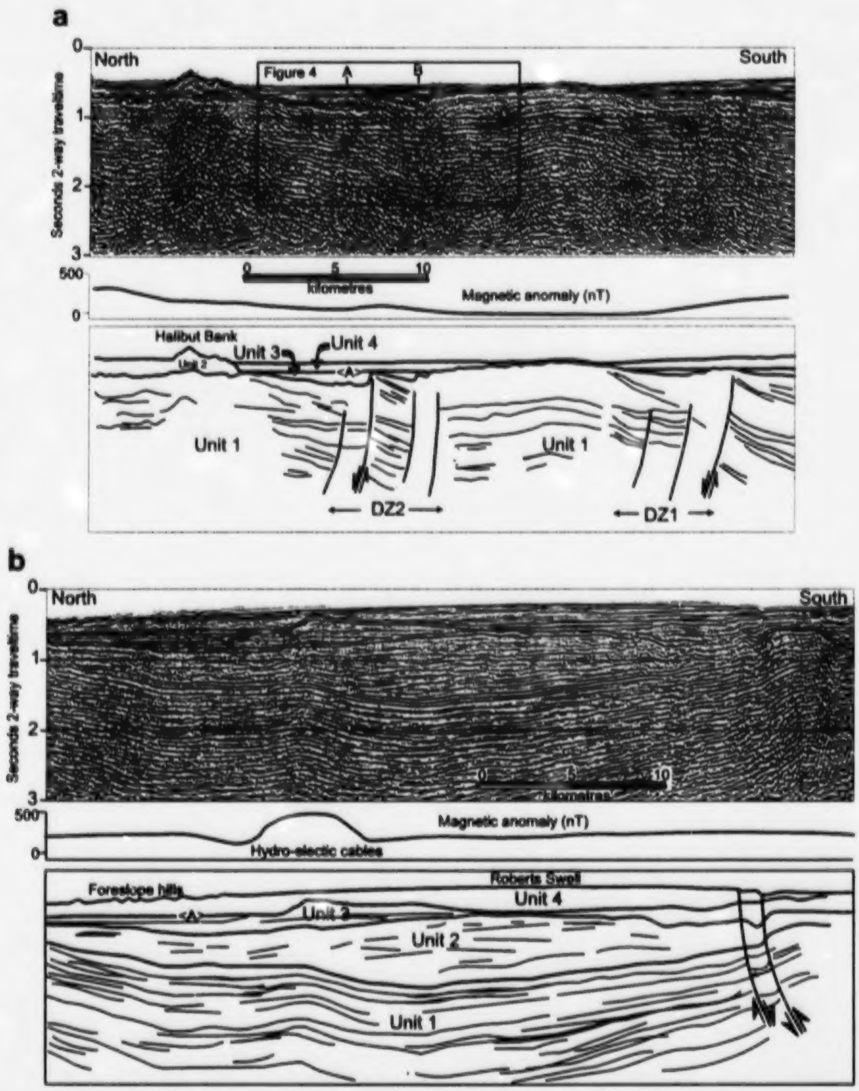

Figure 2. Migrated time section of the SHIPS multichannel seismic (MCS) reflection data (upper) with interpretation (lower) and coincident areomagnetic anomaly along track (centre) (see Fig. 1 for location); a) the northern half of the line, ending at the northern end of the Foreslope hills, and b) the southern portion. Note at least two significant deformation zones where numerous faults are interpreted (DZ1, DZ2). These deformation zones correspond with a change in the magnetic field; the northern one (DZ2) is coincident with a short-wavelength, high-amplitude anomaly, and southern one (DZ1) with a significant magnetic gradient.

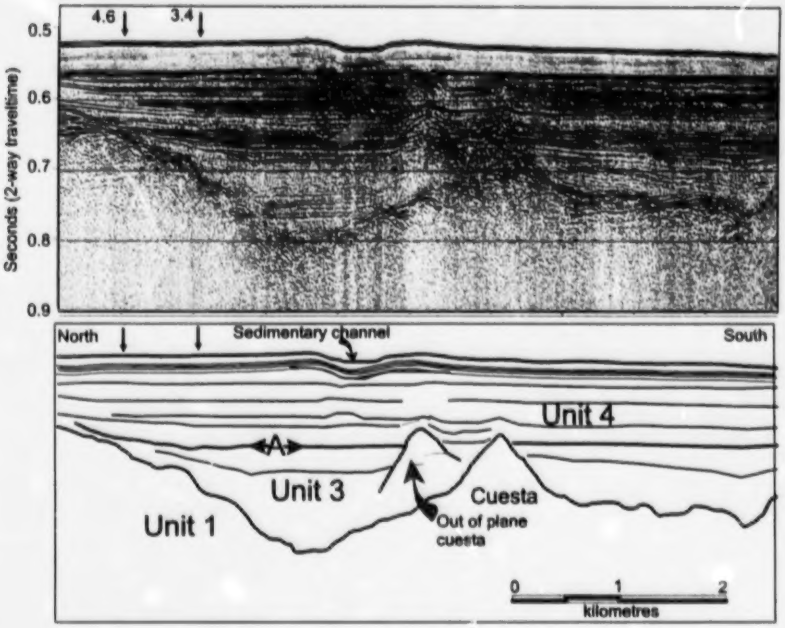

Figure 3.

Single-channel airgun reflection line over the sites of the June 1997 earthquake epicentres. Arrows indicate the mainshock (4.6) and foreshock (3.4) locations. These positions, in absolute terms, have error bars of about 1 km. If the events occurred on a 50°, north-dipping fault plane at 2–4 km depth, as the earthquake studies indicate, then any surficial evidence of the fault would be expected some 1.7–3.4 km south of the epicentre. No unequivocal evidence of faulting or deformation attributable to ground shaking can be noted within the sediment column, but the approximate position does correlate with bedrock cuestas, which are indicative of the deformation zone (DZ2, Fig. 2).

and outwash during the various Pleistocene glaciations. It is thickest (~1200 m thick) just southwest of the Vancouver Deltaport. Internal reflectors do not appear to be folded or faulted as are the underlying reflectors of unit 1, though deformation within this sequence would be difficult to recognize.

The unconsolidated sediment section, comprising units 3 and 4, have been described in detail from high-resolution seismic reflection profiles by Hamilton (1991), Hart et al. (1995), Mosher et al. (1995), and Mosher and Hamilton (1998) (*see* Fig. 3). Unit 3 overlies unconformably the previous two units. The unit infills the deeper troughs and reflections onlap the margins of these troughs. It pinches out completely to the south. Turbidite sequences, resulting from the last episode of glacial outwash, likely comprise the unit. The top of unit 3 is marked by a regionally extensive, high-amplitude, low-frequency, reflection horizon, termed reflector "A" by Mosher and Hamilton (1998).

The uppermost unit in the succession is unit 4. It appears relatively transparent in the SHIPS seismic reflection data but contains high-frequency, low-amplitude coherent, flat-lying internal reflections on high-resolution seismic reflection profiles (Fig. 3). It is thickest in the low-lying regions with a maximum thickness on the order of 200 m, forming an area known as Roberts swell (Fig. 1, 2). This unit represents deposits from the modern Fraser River sediment regime and it occurs extensively throughout the Strait of Georgia.

Earthquake studies

Earthquake focal mechanisms

The June 1997 mainshock (M=4.6) and associated foreshock (M=3.4) beneath the Strait of Georgia provided sufficient data for a well constrained P-nodal solution (Cassidy et al., 1999, in press). Using a total of 73 first motions, a well defined focal mechanism for the mainshock shows thrust faulting along either a north-dipping fault (strike 262°, dip 47°, slip 98°), or along a south-dipping fault (strike 71°, dip 44°, slip 82°) (Fig. 4). For the June 13 foreshock, a total of 34 first motions were useful. The preferred solution is predominantly thrust (Fig. 4) along either a north-northwest-dipping fault (strike 236°, dip 42°, slip 123°), or along an east-dipping fault (strike 15°, dip 56°, slip 64°). This mechanism, however, is not as well constrained as that of the mainshock and a solution with a strike-slip mechanism along an east-striking fault (strike 266°, dip 72°, slip 156°) is possible. The pressure axes for both earthquakes are near horizontal and orientated north-northwest to northwest (346° for the mainshock, 303° for the foreshock), consistent with the overall orientation of P-axes for crustal earthquakes in southwest British Columbia (cf. Wang et al., 1995).

Earthquake hypocentres

The foreshock, mainshock, and aftershock sequence have been relocated as described above (*see* Cassidy et al., in press). These relocated hypocentres fall within a 1.4 km diameter area and in cross-sectional view there is a strong northward-dipping trend (Fig. 4c). The relative locations of these events are very well constrained, with an average of 2σ standard errors of approximately 110–120 m horizontally, and approximately 190 m vertically. The north-dipping structure is particularly evident for the largest (all M>1.5) seven events in the sequence (Fig. 4c). A dip angle of 53° is computed for the northward-dipping plane of aftershocks. This dip angle is in close agreement with 47° for the north-dipping plane in the mainshock focal mechanism solution. The temporal sequence of the relocated events (*see* Cassidy et al., 1999, in press) is

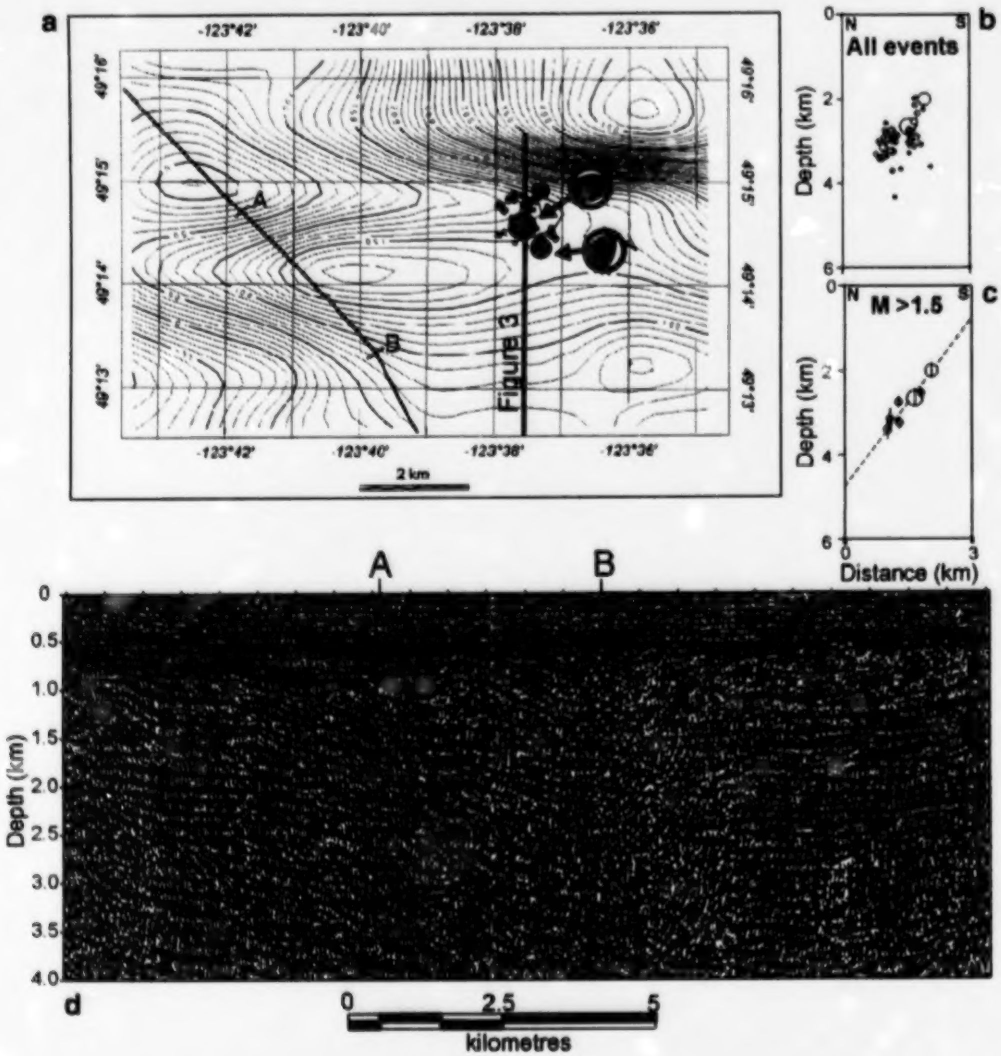

Figure 4. a) Filtered magnetic data in the region surrounding the June 1997 earthquake events (see Fig. 1 for location). Note the east-trending magnetic anomaly with peak amplitudes greater than 170 nT. Stereoplots represent the P-nodal solutions of the foreshock and mainshock events, showing thrust faulting. b) Earthquake hypocentres as determined from advanced location procedures. c) Same as Figure 4b for events M>1.5. Bars for the 2σ errors in the vertical direction are indicated for each event. The horizontal errors (not shown) are approximately one-half those of the vertical. The dotted line is a best fit through these hypocentres showing a dip angle of 53°. d) Migrated depth section of the SHIPS MCS reflection profile through the area shown in Figure 4a. The region between 'A' and 'B' (located on the map and the profile for reference) incorporates the east-trending magnetic anomaly, the cluster of seismic events from June 1997, and corresponds with significant deformation and faulting interpreted from the seismic section.

consistent with downdip rupture, along a north-dipping fault. The mainshock was located downdip, and to the north of the June 13 foreshock, and almost all of the early (within 24 hour) aftershocks were located downdip and to the north of the June 24 mainshock.

Aeromagnetic data

Magnetic anomaly amplitudes in the map area of Figure 1 range from a minimum of -500 nT in the southwest to a maximum of +1660 nT in the northeast. The northwestern portion of the Strait of Georgia is characterized by low (<50 nT) anomaly amplitudes, comparable to those observed over exposures of the Nanaimo Group and Sicker Formation on eastern Vancouver Island. South of Valdez Island, however, anomaly amplitudes are more than 250 nT higher over the western Strait of Georgia, Galiano Island, and northern Saltspring Island. As the Nanaimo Group exposed on these islands is weakly magnetic it suggests the source of the high anomaly values lies in the deeper crust. The transition between the regions of high and low anomaly values extends northeast across the Strait of Georgia from southern Valdez Island to the northern tip of the Foreslope hills, coincident with the seismically defined deformation zone (DZ1, Fig. 2a).

Epicentres of the June 1997 earthquake cluster are located at the western edge of the "Outer Coast Magnetic High" (Haines et al., 1971; Haines and Hannaford, 1974). To enhance subtle magnetic features in this vicinity, an automatic gain filter (Rajagopalan and Milligan, 1994) was applied to the magnetic anomaly data. Enhanced data (Fig. 4) identify the presence of a narrow (approximately 2.5 km wide) east-trending positive anomaly that includes the epicentral location of the June 1997 earthquakes. This anomaly has a strike length of almost 8 km, extending from 1.5 km west of the location of the SHIPS seismic reflection line to just east of the mainshock epicentre.

DISCUSSION

Northern Saltspring and Galiano islands and the southern Strait of Georgia are characterized by a moderately high-amplitude magnetic anomaly. Multichannel seismic reflection data from this region show a thick (>8 km) sequence of sedimentary rocks. High magnetic susceptibility values are not typical of sedimentary rocks, suggesting the anomaly source likely underlies these rocks. The sedimentary package has been deformed into broad, gentle folds in this region. Faulting is not obvious except at the southernmost extent of the line, northeast of Saturna Island.

Beneath the Foreslope hills, seismic reflectors fold upwards. Reflectors can be seen truncating at the bedrock surface just north of the Foreslope hills and there is a loss in record coherency for about 5000 m further north (DZ1, Fig. 2). This deformation zone correlates with a transition in the aeromagnetic data from one of moderately high intensity in the south to low intensity to the north (Fig. 1, 2).

Reflector coherency in unit 1 is regained north of this deformation zone and a slight anticline is observed. These reflectors then terminate abruptly offshore of Gabriola Island in another deformation zone (DZ2, Fig. 2). This latter zone is about 7500 m wide along the line and shows reflectors within it which dip at varying angles, the steepest of which is about 20°E towards the south. This dip occurs on an apparent southern hanging wall of a fault block. The bedrock surface morphology reflects a series of these upturned blocks as cuestas with the steep slope facing north. A number of faults are recognized within this zone as a result of the changing dip directions and offset reflectors. These faults appear as listric normal faults on the seismic profile (Fig. 2). This deformation zone correlates with a narrow, east-trending high-amplitude magnetic anomaly (Fig. 4). The narrow wavelength of the anomaly implies a source body in the near surface. Its amplitude is higher than observed over sedimentary units in the Georgia Basin to the west but comparable to those observed over crystalline rocks of the Coast plutonic complex to the east. The source of the anomaly may be a shallow uplifted block of crystalline basement.

It is within this deformation zone and the coincident magnetic anomaly that the June 1997 earthquakes occurred. The seismic events cannot be positioned on any one particular fault within the zone due to limitations in positioning the events and the fact that the seismic line does not cross the hypocentre. Interpretations of the seismic data indicate a series of steep, apparent north-dipping faults, which are in agreement with the earthquake analyses. In addition, the local east-west magnetic anomaly is in agreement with the strike orientation of the mainshock derived from earthquake analysis. These analyses, however, define a north-south thrust with a northern hanging wall, while the seismic data are interpreted as showing normal faults with southern hanging walls. With a single seismic line crossing these faults, however, the true fault character and true strike and dip cannot be determined.

The critical characteristics of units 2, 3, and 4 over the bedrock deformation zones, from a neotectonics point of view, are that they contain little evidence of faulting or deformation that can be attributed to earthquake ground motion (Fig. 3). Surface rupture would not be expected from the earthquakes of June 1997 even though they were shallow (<6 km depth), because of their small magnitudes (M≤4.6). Little evidence of deformation within Holocene sediments suggests there has been little recent strong, shallow seismicity within these bedrock deformation zones. There are, however, two faults at the southernmost extent of the SHIPS seismic line (north-northeast of Saturna Island) which indicate possible surface rupture.

SUMMARY AND CONCLUSIONS

The SHIPS MCS reflection data through the axial portion of the Strait of Georgia provide the first tentative correlation of shallow geological structure with recent crustal seismicity. The MCS data show broad folding of sedimentary rocks in the southernmost part of the strait. Farther north, are two broad (5–8 km wide) deformation zones, within which reflectors

show changing dip directions, loss of coherency, and offsets interpreted to be normal faults. The northern deformation zone correlates with a distinct east-trending magnetic anomaly interpreted as an uplifted crystalline-basement block. The southern deformation zone is coincident with a steep magnetic gradient. There is no evidence in the Quaternary section above these zones of faulting or sediment deformation. This observation implies that it is unlikely that there have been any large, shallow earthquakes within these zones during the Holocene. Faults with possible surface rupture are apparent farther south.

The northern deformation zone, 30 km west of Vancouver, correlates with a region of frequent historic shallow crustal seismicity. The mainshock and associated foreshock and aftershocks of an earthquake recorded at this site in June 1997 have been analyzed in detail. Results describe a shallow (2–4 km) thrust on a north-dipping (~50°), east-trending fault plane. Seismic reflection interpretations agree with this dip determination and the strike orientation corresponds with the trend of the magnetic anomaly in this zone.

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